

## **Northern Indian Ocean Salt Transport (NIOST): Estimation of Fresh and Salt Water Transports in the Indian Ocean using Remote Sensing, Hydrographic Observations and HYCOM Simulations**

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### **LONG-TERM GOALS**

While the Indian Ocean's important contribution to global salt and heat budgets is well known to the scientific community, quantified analyses of its physical dynamics are underrepresented in the literature. Here we use the newly launched Aquarius satellite derived Sea Surface Salinity (SSS) data as well as Argo salinity profiles, model simulations and reanalysis products are used to quantify volume, salt, and freshwater transports in both the Arabian Sea (AS) and Bay of Bengal (BoB) and to examine the salinity structure and advection during the two annual monsoon seasons.

### **OBJECTIVES**

1. To estimate near surface salt transport using satellite and *in situ* salinity observations and compare with HYCOM simulated near surface salinity fields, and obtain depth- integrated salt transport from HYCOM.
2. To address the salinity variability at intraseasonal, interannual and decadal time scales and its impact on the circulation and particularly the coastal currents.
3. To study of role of salinity on the barrier layer dynamics in the Bay of Bengal (BoB), Arabian Sea (AS) and Equatorial Indian Ocean (EIO).
4. To study the role of the coastal Kelvin waves on the fresh and salt water transports.

### **APPROACH**

#### **Basin-scale Exchange of salt and Fresh water between the Arabian Sea and the Bay of Bengal during Monsoons**

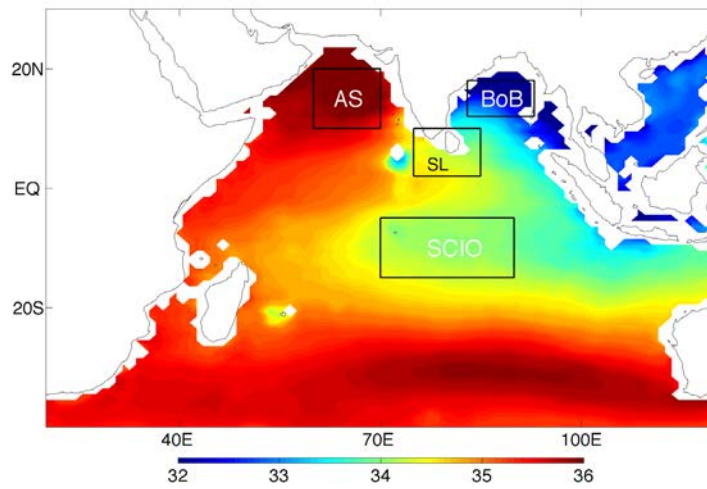
In the third year of this project we looked at the basin-scale exchange of salt and fresh water between the Arabian Sea and the Bay of Bengal during Monsoons. The Northern Indian Ocean (NIO) presents a unique dipolar sea surface salinity (SSS) structure with the salty Arabian Sea (AS) on the west and the fresher Bay of Bengal (BoB) on the east. At the surface, the largest driver of seasonal salinity variability is the monsoonal riverine run off and winds and their ability to transport volume between the two basins. Salt and freshwater fluxes show a strong semi-annual zonal variation between the two basins along south of Sri Lanka. Using a combination of observational data (Aquarius salinity, Argo

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floats and hydrographic data collected different cruises), various reanalyses (ECCO2, SODA, ORAS4), and HYCOM simulations over the 4 year period from January 2008 to December 2011 (as shown in Table 1), the upper 200 m layer salinity structure of this contrasting, yet interconnected, region is quantified.

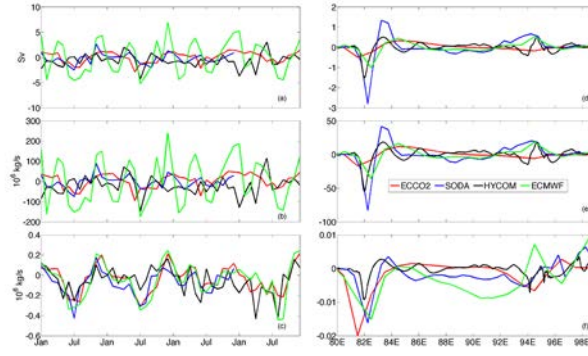
## PRELIMINARY RESULTS

Figure 1 shows the mean Aquarius SSS during August 2011-May 2014 and several boxes that were selected for examining various aspects of the salinity dynamics within the NIO. These sub-regions are chosen based on the differing physical dynamics of the NIO as a whole. The boxes are used to generate box-averaged salinity versus depth profiles to gain additional insight into how salinity changes with depth on seasonal and year-to-year time scales.

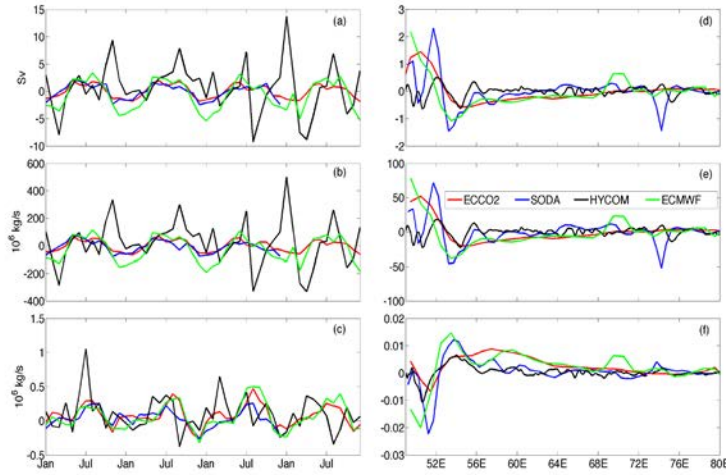


**Figure 1. Mean Aquarius level 3 SSS between August 2011 and May 2014. The boxes denote regions that will be examined, where AS is the Arabian Sea (60-70°E, 10-20°N), BoB is the Bay of Bengal (83-93°E, 12-18°N), SL is Sri Lanka (75-85°E, 2-10°N), SCIO is the South Central Indian Ocean (70-90°E, 15-5°S). Also along the 6°N cross-sections in both the AS and BoB wherein volume, salt and freshwater fluxes are presented.**

Meridional depth-integrated salt, freshwater, and volume transports along a slice of each basin at 6°N reveal the seasonal variability in each basin. In the AS (Figure 2), maximum volume transport of  $\sim 3$  Sv occurs towards the north in July when the Somalia current is at its peak. In the BoB (Figure 3), southward volume transport of  $\sim 3$  Sv occurs during the same period. Neither the southwest nor northeast monsoon current dominates the transport profile of either basin at this latitudinal cross-section. Regional salt budgets reveal the seasonality of each advection term. The BoB shows the largest seasonal variability in salinity with changes up to  $\sim 0.5$  psu/month during the northeast and southwest monsoons.



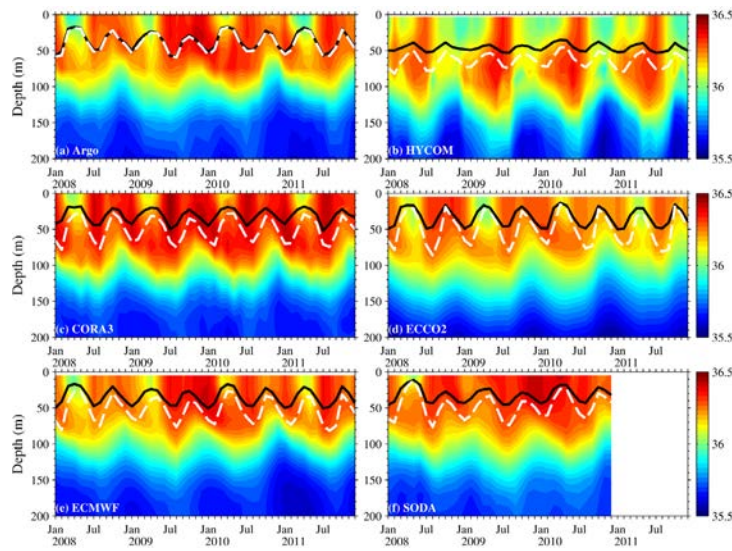
**Figure 2. Monthly time-series of depth-integrated Arabian Sea volume (a), salt (b), and freshwater (c) transports ( $\times 10^6 \text{ kg s}^{-1}$ ) across  $6^\circ\text{N}$  section between 2008 and 2011 along with the mean depth-integrated volume (d), salt (e), and freshwater (f) transports at the longitudes within the Arabian Sea between 2008 and 2011.**



**Figure 3. Monthly time-series of depth-integrated Bay of Bengal volume (a), salt (b), and freshwater (c) transports ( $\times 10^6 \text{ kg s}^{-1}$ ) across  $6^\circ\text{N}$  section between 2008 and 2011 along with the mean depth-integrated volume (d), salt (e), and freshwater (f) transports at the longitudes within the Bay of Bengal between 2008 and 2011.**

The salinity variability of the major sub-regions of the NIO continues at depth. Figure 4 shows the time-depth section of AS salinity for Argo and all models under consideration. The MLD and the isothermal layer depth (ILD) are overlain on the plots. The vertical gradient is approximately 1 psu between the surface and 200 m, with highest salinity at sea surface. Gravitational stability then demands overturning within the water column. This means that temperature maximum must occur close to the surface to prevent the overturning of the water column. Indeed, a time-depth profile of temperature for the same region (not shown) shows an annual surface temperature between  $27^\circ$  and  $30^\circ\text{C}$  with decreasing temperature with depth. This surface temperature maximum provides the density adjustment necessary to keep the vertical salinity gradient from overturning.

There appears to be little model disagreement with respect to this vertical gradient. Low salinity water can be seen at the ocean surface on a seasonal basis centered around the monsoon transition periods. Among all the model products there is disagreement in the salinity magnitudes and the time of occurrences of high salinity. HYCOM (Fig 4b) shows the seasonal occurrence of the largest plume of low salinity waters in the upper 50 m layer, as compared to the Argo salinity. SODA and also CORA3 (Figures 4c, 4f) shows almost no decrease in salinity at the surface on a seasonal cycle. Finally, both the MLD and the ILD share the seasonality of the anomalous decrease in surface salinity during boreal spring. The models disagree on how deep each layer should be but all products, excluding HYCOM (Fig 4b), show a decrease in the layer thickness in boreal spring and fall and an increase in layer depth during the peak of the NEM and SWM. Barrier layer thickness (BLT= ILD-MLD) exhibits strong seasonality with larger thickness up to 25 m during each monsoon season and decreased thickness during monsoon transitions. Please check the Argo MLD and ILD values. Argo should show the BLT variation. Earlier studies have shown the importance of barrier layer dynamics in the AS, most notably in the South Eastern Arabian Sea (SEAS) warm pool (Nyadjro et al., 2012).

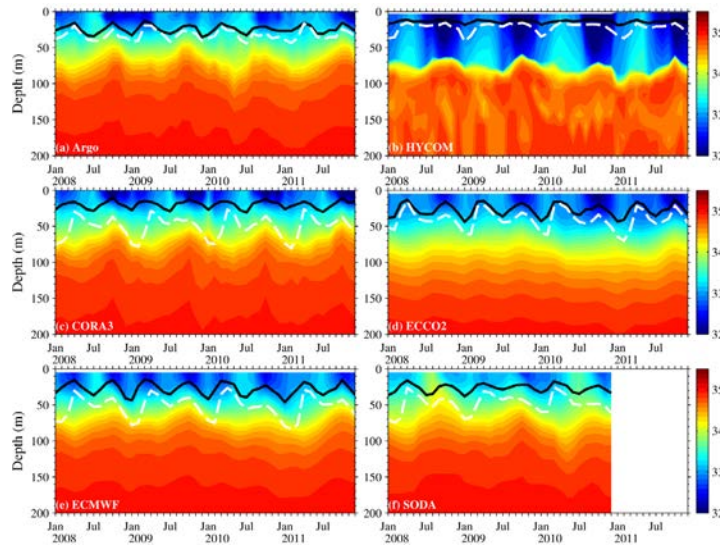


**Figure 4** Time-Depth sections of salinity in the Arabian Sea, mixed layer depth (black line), and isothermal layer depth (white dashed line) between January 2008 and December 2011 from Argo (a), HYCOM (b), CORA3 (c), ECCO2 (d), ECMWF (e), and SODA (f).

Figure 5 shows the time-depth salinity structure for the BoB. A shallow lens of low salinity water occurs with a seasonal cycle that peaks during the NE monsoon. All products have the lowest vertical depth of the freshwater lens up to 50 m with the exception of HYCOM which reaches slightly further down to around 75 m. HYCOM produces very low salinity waters and SODA produces relatively higher salinity waters, compared to Argo salinity. Between the SW and NE monsoon transition, freshest water appears at the surface, and the mixed layer thickness is small. This adjustment in the thermocline brings with it salty waters from below and allows for the entrainment of higher salinity values into the upper 50 m of the water column. It should be noted that this mixing event does not extend up to the surface and is not the salt pump alluded to by Vinayachandran et al., (2013). The BLT appears to have low seasonality in the products of Argo, HYCOM, and ECCO2. The products of CORA3, ECMWF and SODA show thicker (40 m) BLT. The studies of Felton et al., (2014) support the results of the model products of BLT in the BoB with the highest annual mean BLT in the northern



BoB. The mixed layer of this region is often flush with low salinity waters due to its close proximity to large riverine output and higher rates of E-P (Sengupta et al., 2006). This positive buoyancy at the surface inhibits mixing of both colder and saltier waters from below. This process sets up a feedback mechanism that keeps the BoB surface waters perpetually warm which allows for more convection and in turn more precipitation. This flux of freshwater at the surface keeps the water column highly stable and thus perpetuates the cycle (Drushka et al., 2014). Below freshwater layer exists a strong vertical salinity gradient as the salinity transitions from  $\sim 33$  psu or less to 35 psu in only a few tens of meters. This layer of salty water likely originates in the AS. Vinayachandran et al., (2013) showed that salty AS water transported into the BoB tends to sink to approximately 200 m depth where it then stays unless forced to the surface by the seasonal salt pump.



*Figure 5 Time-Depth sections of salinity in Bay of Bengal, mixed layer depth (black line), and isothermal layer depth (white dashed line) between January 2008 and December 2011 from Argo (a), HYCOM (b), CORA3 (c), ECCO2 (d), ECMWF (e), and SODA (f).*

**Table 1. Summary of the characteristics of model outputs used in this study**

Product	ECCO2	HYCOM	ORAS4	SODA
Version	Cube 78		System 4	2.2.4
Model	Massachusetts Institute of Technology (MIT) General Circulation Model (MITgcm)	Miami Isopycnic Coordinate Ocean Model	Nucleus for European Modeling of the Ocean version 3 (NEMO3)	Parallel Ocean Program version 2 (POP2)
Horizontal resolution	18 km ×18 km	0.08°×0.08°	1°×1° with equatorial refinement (0.3°)	0.25°×0.4° (average)
Vertical levels	50	32	42	40
Assimilation method	Green's function optimization	NCODA 3DVAR with MODAS synthetics	Multivariate optical interpolation (OI)	OI
Data assimilated	Altimetry, Temperature (T) and Salinity (S) profiles from XBT, CTD, Argo, in-situ sea ice concentration	Altimetry, satellite SST and SSS, in situ T, S profiles from XBT, Argo, and moored buoys	Altimetry, T & S from XBT, CTD, Argo, and moorings	Altimetry, satellite and in-situ SST, T & S profiles from MBT, XBT, CTD, Argo, TAO and other buoys
Period	1992-2012	2003-2011	1958-2011	1958-2010
Laboratory	National Aeronautics and Space Administration (NASA)	Naval Research Laboratory (NRL)	European Centre for Medium-Range Weather Forecasts (ECMWF)	Texas A&M University and University of Maryland
Data download	<a href="ftp://ecco2.jpl.nasa.gov/data1/cube/cube92/lat_lon/quart_90S_90N/">ftp://ecco2.jpl.nasa.gov/data1/cube/cube92/lat_lon/quart_90S_90N/</a>	<a href="http://hycom.org/dataserver/glb-analysis">http://hycom.org/dataserver/glb-analysis</a>	<a href="ftp://ftp.icdc.zmaw.de/EASYInit/ORA-S4/monthly_1x1/">ftp://ftp.icdc.zmaw.de/EASYInit/ORA-S4/monthly_1x1/</a>	<a href="http://dsrs.atmos.umd.edu/DATA/soda_2.2.4/">http://dsrs.atmos.umd.edu/DATA/soda_2.2.4/</a>
References	Menemenlis et al. 2008	Chassignet et al. 2003; Metzger et al., 2014	Balmaseda et al. 2012	Carton and Giese 2008

## RELATED PROJECTS

None

## PUBLICATIONS

### *Refereed Publications*

D'Addezio, J.M., B. Subrahmanyam, E.S. Nyadjro, V.S.N. Murty (2014). Basin-scale Exchange of Salt and fresh water between the Arabian Sea and the Bay of Bengal during monsoons, Journal of Physical Oceanography (in preparation).

Nyadjro, E.S., and B. Subrahmanyam (2014). SMOS salinity mission reveals salinity structure of the Indian Ocean Dipole, IEEE Geoscience and Remote Sensing Letters, vol 11,9, 1564-1568.

Felton, C.S., B. Subrahmanyam, and V.S.N. Murty (2013). ENSO-Modulated Cyclogenesis over the Bay of Bengal, Journal of Climate, 26, 9806-9818.

Nyadjro, E.S., B. Subrahmanyam, and B.S. Giese (2013). Variability of Salt flux in the Indian Ocean during 1960-2008, Remote Sensing of Environment, 134, 175-193.

Subrahmanyam, B., G. Grunseich, E.S. Nyadjro (2013). Preliminary SMOS Salinity measurements and validation in the Indian Ocean, IEEE Transactions Geoscience and Remote Sensing, 51, 1, doi:10.1109/TGRS.2012.2199122.

### *Conference/Workshop presentations*

- **Subrahmanyam, B.** and E.S. Nyadjro (2014). Estimation of Fresh and Salt Water Fluxes and Transports in the Indian Ocean using satellite observations and model simulations, EGU conference, Vienna, Austria 27 April-2 May, 2014.
- **Subrahmanyam, B.** and G. Grunseich (2013). Integrated multi-mission satellite altimetry data in climate studies-Detection of the Madden-Julian Oscillation, Ocean Surface Topography Science Team (OSTST) Meeting, October 7-11, 2013, Boulder, Co.

## HONORS/AWARDS/PRIZES

2014 Victoria Young has been awarded USC's Magellan award.

2014 Clifford Felton awarded M.S degree (Spring, 2014).